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Improvements to the High-Frequency Benchmark Propagation Analysis Program

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INTRODUCTION

The High-Frequency Benchmark is a computer code being developed to employ a sophisticated ray tracing program coupled with a state-of-the-art ionospheric model of the user's choice. The merging of these two major components depends critically on the development of a spatial smoothing routine that accepts arbitrary ionospheric models as input. Such a spatial smoothing routine was developed by Paul (1991) and implemented in the Benchmark (Ferguson and Shellman, 1991). This report describes improvements and enhancements to that computer program.

Most models of high-frequency (HF) propagation rely on synoptic data to develop global maps of key propagation parameters such as the maximum useable frequency (MUF). One failing of this approach is that large errors in prediction of critical propagation parameters occur under many important conditions. This is especially true at high latitudes. In part, errors in the models may be attributed to the fact that they are based almost exclusively on hourly averages taken at mostly middle latitude stations. Another important contribution to errors is the lack of reliable models of intermittent phenomena such as sporadic-E. The most widely used HF prediction codes in use have no provision for first principles, physics-based calculations. In the past, first principles codes were too slow, complex, and user-unfriendly to address most classes of problems of interest to HF communicators and model developers. Today, modern desktop computers rival the mainframes of the past, and the prospect of using modern first principles codes in routine propagation problem solving is a reality. Future HF prediction models will be hybrids of rigorous physics-based propagation, expert systems to monitor and interpret realtime geophysical and ionospheric sensors, and improved man-machine interfaces.

The goal of the work described in this report is to develop techniques that permit timely and efficient evaluation of different propagation models. The resulting program is to be as sophisticated as possible with concerns for computer run time to be subordinate to the use of realistic models of the environment. Employed with new databases of high-latitude propagation measurements, this model will be used to evaluate and improve the faster running models and point to deficiencies in the ionospheric models. In addition, the development of new graphical displays will enhance understanding of the propagation environment.

SPATIAL SMOOTHING

The first step in the development of the HF Benchmark was to develop a generalized spatial smoothing routine that would accept arbitrary ionospheric profiles. A candidate spatial smoothing algorithm was developed by Paul (1991), who demonstrated a general function that permitted fitting a set of irregularly spaced discrete data with satisfying results. Ferguson and Shellman (1991) applied this algorithm to a three-dimensional array of ionospheric profiles of electron density with altitude, distributed in an irregular grid of latitude and longitude. Modifications have been made to that application. For completeness, this algorithm will be reviewed.

The basic procedure in this algorithm is to define an ionospheric parameter at a series of coordinates. The earlier version of the program used the logarithm of the electron density. Currently, the program is using the logarithm of the plasma frequency. A single data point is characterized by a function, f_i, where

$$f_i(x,y,z) = 1 + \frac{a_i}{1 + \left(\frac{x - x_i}{r_{xi}}\right)^2 + \left(\frac{y - y_i}{r_{yi}}\right)^2 + \left(\frac{z - z_i}{r_{zi}}\right)^2}$$

and the value at a point (x,y,z) due to all of the data points in the set is given by

$$p(x,y,z) = p_o + p_s \prod f_i(x,y,z).$$

The quantities r_{xi}, r_{yi}, and r_{zi} are called the control distances and basically determine the range of influence of individual data points. These control distances should be about 80% of the separation of the data points in each direction. The quantities p_o and p_s are scaling parameters. We use them to normalize f_i and to force its range of values to be between 0 and 1. This seems to improve the convergence of the iterations used to find the values of the unknown coefficients, a_i.

Modifications to the original procedure of Paul (1991) were required to consistently achieve convergence of the coefficients. Given that there is no functional form to impose on the iterations, the following procedure is used. The minimum value of the electron density data is determined (p_o) and subtracted from all of the values. These data are then normalized using the peak value of the offset data (p_s). Equation 2 is used to compute a value at each of the input locations. A correction term is defined equal to the difference between the computed and input values of the ionospheric parameter at the input locations. If the largest of these correction terms is less than a specified amount, then the iterations are terminated. Otherwise, the coefficients are adjusted by some fraction and the calculations repeated. Currently, we are using a maximum difference between these calculations and the input data of 0.05, which amounts to 5% of the logarithm of the peak plasma frequency and gives reasonable results. The large number of data points required to give a reasonable representation of the ionospheric variation along a propagation path still requires a large number of iterations. Typically, quite a few iterations are required to resolve individual data points and that the convergence is slow (many iterations). In spite of this slow convergence, using a larger adjustment factor at these times causes the iteration process to fail. It seems that we must always use a small fraction to adjust the coefficients (0.03125 in the current configuration of the program). This small value prevents oscillatory behavior of the iterative corrections but requires a lot of iterations. After much experimentation, we found that the initial estimate for the a_i should be some fraction of the quantity $d_i - 1$. Currently the program uses 0.6 for this fraction.

Three subroutines are used to implement the interpolation. The routine *AKP_MODEL* takes the initial path parameters and sets up the array of data points by calculating the locations of the ionospheric profiles. The routine *AKP_COEFF* finds the quantities p_o and p_s, and perfoıms the iterations to determine the coefficients, a_i. The routine *AKP_XYTHPH* does coordinate conversion between the magnetic dipole coordinate system used in the ray trace routines and the quasi-Cartesian coordinate system used in the interpolation routine. This routine also calculates the derivatives of the ionospheric parameters due to the spatial variation of the ionosphere.

IONOSPHERIC MODEL

The ionospheric model currently used in the program is the Utah State University (USU) ionospheric model, a parameterized version obtained from Anderson*. This model is called the High Latitude Ionospheric Specification Model (HLSIM). A driver subroutine named *USU_MODEL* has been developed for this model. This routine is called by *AKP_MODEL* to generate ionospheric profiles at points 500 km apart along the propagation path (defined by the transmitter and the receiver) and at points 500 km away on either side of the path along a direction perpendicular to the propagation path. The previous model calculated the ionospheric parameters at heights determined by the HLISM model that are closer together at the bottom of the ionosphere than at the top. The heights passed to the spatial smoothing routine were evenly spaced, having been interpolated from these irregularly spaced values. The current version of the program now uses the values as returned from the ionospheric model. This gives more accurate values of the details of the ionospheric parameters at low altitudes, as originally intended for the HLISM.

The HLISM is used because it is considered to be one of the best high-latitude models available. Unfortunately, it is a model for positive ion densities in the altitude range from 100 to 800 km. To get electron density, charge neutrality is invoked and the electron density is set equal to the total ion density. This is valid only where the negative ions can be ignored. The model tends to generate (correctly) large ion densities at the bottom of the ionosphere that would normally be neutralized by the presence of negative ions as well as electrons at those altitudes. For the moment, an adjustment to the model has been made to force the electron density to decrease with altitude below the ionosphere. The user selects a minimum height at which the ionospheric density is computed. Two additional heights, separated by 20 km, are added below this height that force a decade decrease in the plasma frequency at each lower (additional) altitude. Under nighttime conditions, these values may cause a slight kink in the electron density profile. The adjustment is required to provide a gradual entry into the ionosphere for the ray tracing routine. The unrealistically high values of electron densities at the bottom of the ionosphere were causing numerical problems in the ray tracing. We plan to obtain and implement an electron density model either as a modification of the USU model or as a replacement. A new ionospheric model based on the Parameterized Realtime Ionospheric Specification Model (PRISM)** will be implemented. The new model, the Parameterized Ionospheric Model (PIM), differs from PRISM in not being realtime. However, it is a global model and will give the Benchmark a global ionospheric model suitable for a variety of propagation studies.

* Private communication with D. Anderson, 1991.

** Private communication with Daniels, 1992.

RAY TRACING

As in Ferguson and Shellman (1991), the HF Benchmark continues to use the Jones and Stephenson (1975) ray tracing model. This is a versatile program with full allowance for externally specified models of the electron density, collision frequency, and geomagnetic field. Every effort has been made to retain this flexibility in its implementation in the Benchmark. In particular, the input requirements are nearly identical to the original Jones and Stephenson version, with the spatial smoothing algorithm being specified as an ionospheric model named "*AKPMODEL.*" When the program sees "*AKPMODEL*" as the ionospheric model, the next input record is read as a case identification, for example *CASE-ID*, and forms the root of the file name for all subsequent outputs. For example, the parameters of the ray paths are stored in a file of the name "*CASE-ID.TMP*," and the file named "*CASE-ID.002*" contains an information log. In addition to the original program inputs, additional parameters have been introduced. These parameters are summarized in table 1. If the value of parameter 100 is 9, the program looks for a file with the name of the case and the extension AKP. The coefficients and other parameters are read from this file. This is illustrated in the sample input file shown below.

Table 1. Ray trace inputs for AKP model.

Index	Value	Usage
100	1	This value used to signal that the a_i need to be computed (9 indicates that the a_i have been computed previously).
111	1	Number of the month (Jan is 1).
112	31	Day of the month.
113	1991	Year.
114	1200	UT in HHMM format.
115	100	10-cm flux.
116	1	k_p
117	1	Sign of B_y (1 for "+"; -1 for "-").
118	120	Minimum *USU_MODEL* height to use (km).
119	400	Maximum *USU_MODEL* height to use (km).
120	0.8	Horizontal control distance factor.
121	0.8	Vertical control distance factor.
122	0.6	Initial scale factor for a_i.
123	6.0	Range of influence factor.
124	0.03125	Iteration adjustment factor.
125	0.05	Maximum error to terminate iterations.
126	501	Maximum number of iterations.
130		Plot of ionospheric parameters; =0 no output; =1 logarithm of electron density; =2 plasma frequency; =3 X=1, X+Y=1, X-Y=1.
131	2	Plasma frequency.
132	200	Height at which t. do the horizontal contours of the ionospheric parameter.

Minor procedural modifications have been made to facilitate running this program on a PC but the FORTRAN used in the program is not specific to that platform. In fact, an identical capability exists for a VAX.

SAMPLE PROBLEM

A sample problem is presented here to illustrate the unification of the individual models. The path is defined in geographic coordinates from 68.5°N, 32.5°E to 55.5°N, 117.1°W. The geographic bearing angle is 339.3°, and the path length is 6000 km. The ionospheric profiles are generated for 23 December at 0215 UT. The 10-cm flux is 70, the k_p is 2, and the direction of the sun's magnetic field, B_y, is positive. The input parameters for the program are shown in figure 1. Contour plots of the plasma frequency in the vertical plane along the path are shown in the top panel of figure 2, and contours of the plasma frequency in the horizontal plane at an altitude of 200 km are shown in the bottom panel. This display is generated by an auxiliary program named PLOTPATH. This program uses the same input as the Benchmark and calculates the selected ionospheric parameter using the file containing the calculated coefficients. It is clear that the ionosphere is changing in all three dimensions. In particular, we note a broad maximum near 2000 km followed by a constriction of the contour lines near 3500 km.

Ray paths for the ordinary ray at 3 MHz are shown in figure 3. The initial elevation angles are 20° and 50°. The top panel shows the projection of the ray paths onto the vertical plane passing through the transmitter and the receiver. The ray with a small circle on its end (elevation 50°) is a ray that penetrates the ionosphere. The bottom panel of figure 2 shows the projection of the ray paths onto the ground with locations above the horizontal axis being to the west of the propagation path. We see that the off-path variation of the ionosphere causes some deflection of the ray paths. Ray paths for the extraordinary ray at 3 MHz are shown in figure 4. As in figure 3, the elevation angles are 20° and 50°. However, the ray at 50° does not penetrate but does show a strong deflection from the direct path. Figures 5 and 6 show ray traces for this path at 4 MHz at elevation angles of 0° and 30°. We see that the ray at 0° becomes a grazing ray and never reaches the earth's surface. The ray at 30° shows a very nonuniform pattern of earth and ionospheric reflections, confirming the nonuniform ionosphere indicated in figure 2.

IONOSPHERIC DISPLAYS

Two ionospheric displays have been developed. One of the displays is a global view showing contours of the ionospheric profile in a fixed meridian, and the other is a view along short paths (a subset of the global view). In each display, contours of the electron density are shown, taken directly from the ionospheric model. Figure 7 shows an example of the global display. The map projection is orthographic, with the observation point in the center of the display. The location of this point is specified by the user. Superimposed on the circle representing the earth is a series of lines indicating land masses. There is also a series of lines ranging from solid, through dashes of various lengths, to dotted. These lines indicate the position of solar zenith angles ranging from 90° (solid) to 99° (dotted) to show where the day-night transition is located. If it is visible from the observation side of the globe, the sub-solar point is also shown. The vertical scale for points above the earth's surface is specified by the user by setting the number of inches between the earth's surface and the top of the model ionosphere. Because the model ionosphere is strictly valid at high latitudes, the strange features shown at middle and equatorial latitudes must be ignored. Nevertheless, the auroral bulges are visible, and the differences between the daytime and nighttime ionospheres are evident. The second display, shown in figure 8, is a modification of the first. The primary difference from the global display is the shorter path length, which allows scaling of the vertical dimension closer to the horizontal dimension. The user specifies all other parameters.

PROBLEMS AND FUTURE PLANS

Unfortunately, the main problem noted for the first program remains; namely, the iteration process required to obtain the coefficients for the interpolation model is excessive in computer time, and the interpolation is quite slow. A faster method is highly desirable. The current interpolation model still requires too much manual adjustment to be routinely used. The ionospheric model needs to be changed to give more realistic electron densities in the lower altitudes. This problem will be addressed by the acquisition of the newer ionospheric model PIM. This latter effort is very important if the Benchmark program is to properly account for absorption. The ray trace model has some difficulty with the radical changes introduced by the ionospheric model. Modifications have been made to the ray tracing, but additional refinement of its procedures are probably necessary.

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Ferguson, J. A., and C. H. Shellman. 1991. "Spatial Smoothing of Ionospheric Parameters for use in the High-Frequency Benchmark Propagation Analysis Program," NOSC TR 1469 (Nov). Naval Ocean Systems Center, San Diego, CA.

Jones, R. M., and J. J. Stephenson. 1975. "A Versatile Three-Dimensional Ray Tracing Computer Program for Radio Waves in the Ionosphere," U. S. Dept. of Commerce Office of Telecommunications Report 75-76, (Oct).

Paul, A. K. 1991. "Fitting of Discrete Irregularly Spaced Discrete Data with Differentiable Functions: Application to Ray Tracing in the Ionosphere," NOSC TR 1405 (Mar). Naval Ocean Systems Center, San Diego, CA.

akpmodel			Ionospheric model name
w31a			AKP Model coefficients file (AKP extension)
			Ionospheric perturbation name
diploy			Geomagnetic field model name
expz			Collision frequency model name
Transpolar path			
1	-1.		Ray type: 1=Ordinary; -1=Extraodinary ray
7	3.		Initial frequency, MHz
8	4.		final frequency
9	0.		step in frequency
11	339.25	deg	Initial azimuth angle, clockwise from north
12	339.25	deg	final azimuth angle
13	5.	deg	step in azimuth angle
15	0.	deg	Initial elevation angle
16	30	deg	final elevation angle
17	5.	deg	step in elevation angle
3	0.		Transmitter height, km
4	68.5	deg	transmitter latitude, north
5	32.5	deg	transmitter longitude, east
18	0.		receiver height above the earth, km
19	55.5	deg	receiver latitude
20	-117.1	deg	receiver longitude
82	68.5	deg	left latitude of plot
83	32.5	deg	left longitude of plot
84	55.5	deg	right latitude of plot
85	-117.1	deg	right longitude of plot
87	300.		horizontal projection ymax, km
100	1.		Electron profile file: =1 compute; =9 read from file
110			Input for USU ionospheric model
111	12.		number of the month
112	23.		day of the month.
113	1991.		year
114	0215.		UT in HHMM format.
115	70.		10 cm flux
116	2.		k_p
117	1.		index for sign of By: =1 for '+'; =-1 for '-'
118	120.		ht minimum
119	400.		ht maximum
120			Iteration factors for AKP model
121	0.8		factor range
122	0.8		factor height
123	0.6		factor A
124	12.5		factor xyz
125	0.03125		factor iter
126	0.05		maximum error to stop iterations
127	1001.		maximum number of iterations
130			Plot of ionospheric parameters
130			=0. no output
130			=1. LOG10(Ne)
130			=2. plasma frequency
130			=3. X=1, X+Y=1, X-Y=1

Figure 1. Input parameters for the sample (transpolar) path.

131	2.	Plasma frequency.
132	200.	height at which to do horizontal contours
		A blank in columns 1-3 ends the current input
STOP		End of run

Figure 1. Input parameters for the sample (transpolar) path (continued).

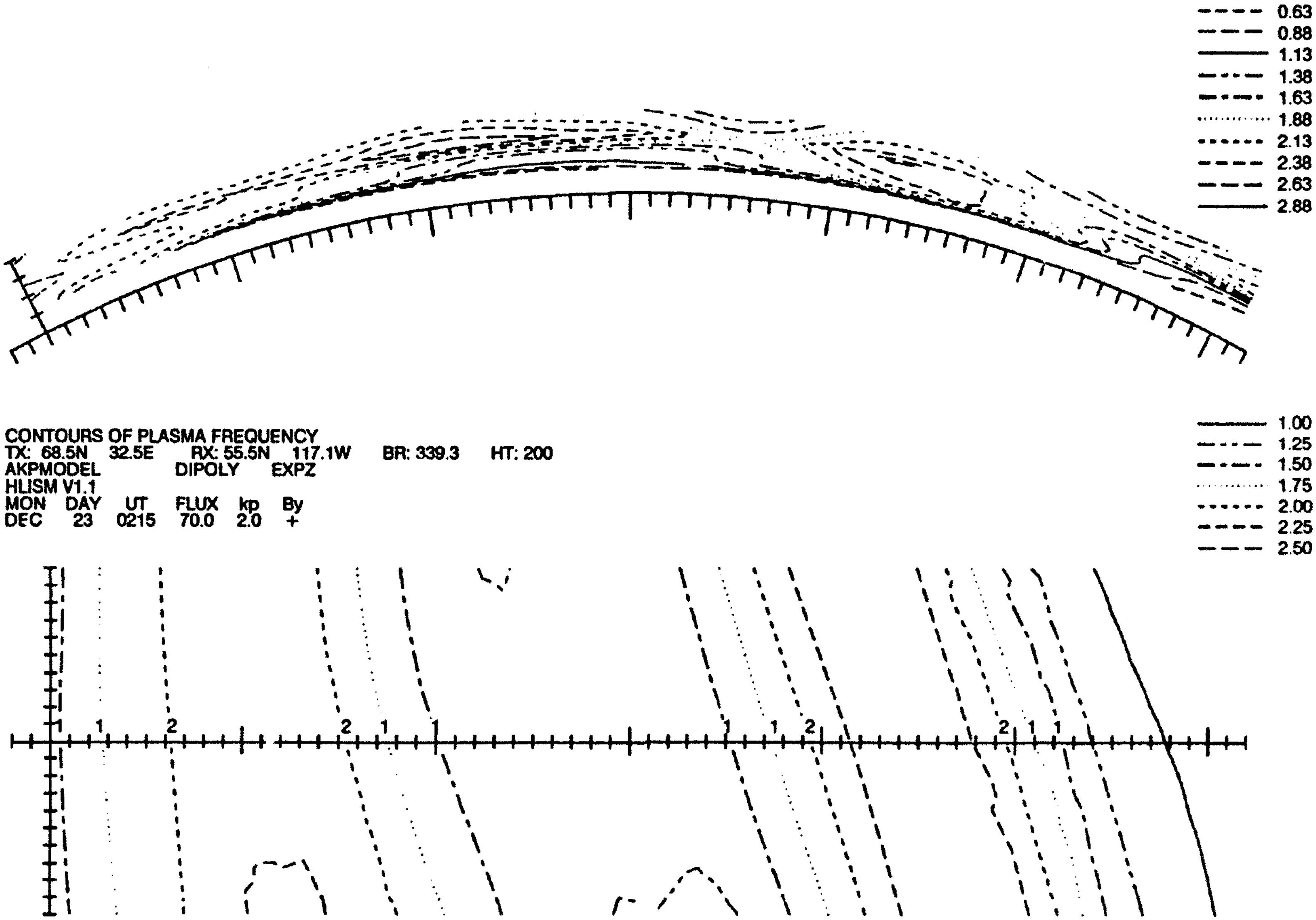

Figure 2. Plots of contours of constant values of the logarithm of the plasma frequency in the vertical plane along the great circle path passing through the transmitter and receiver and in the horizontal plane at 200 km.

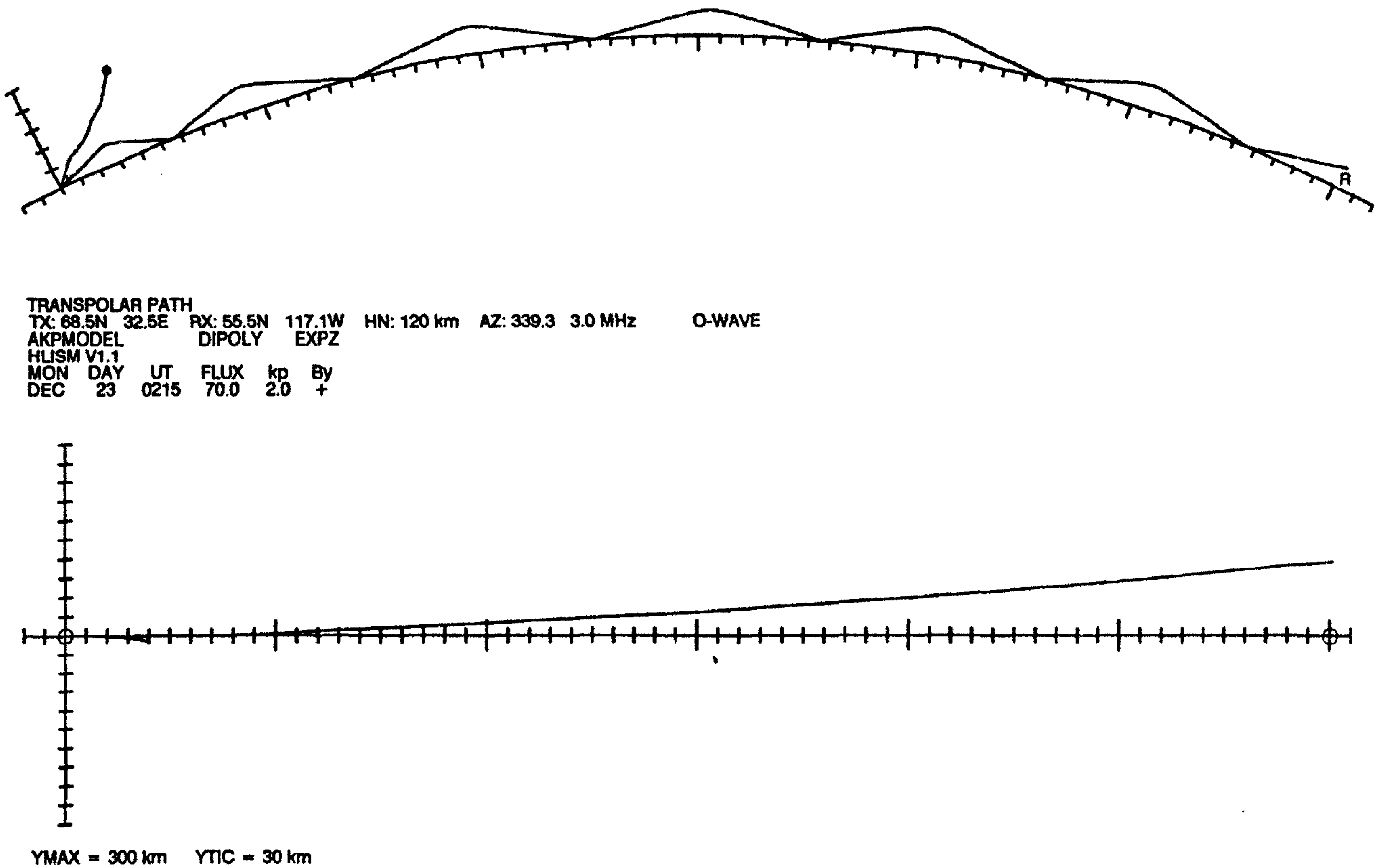

Figure 3. Plots of the ray paths for the ordinary ray at 3 MHz in the vertical plane passing through the transmitter and the receiver (top panel) and in the horizontal plane (bottom panel). The elevation angles are 20° and 50°.

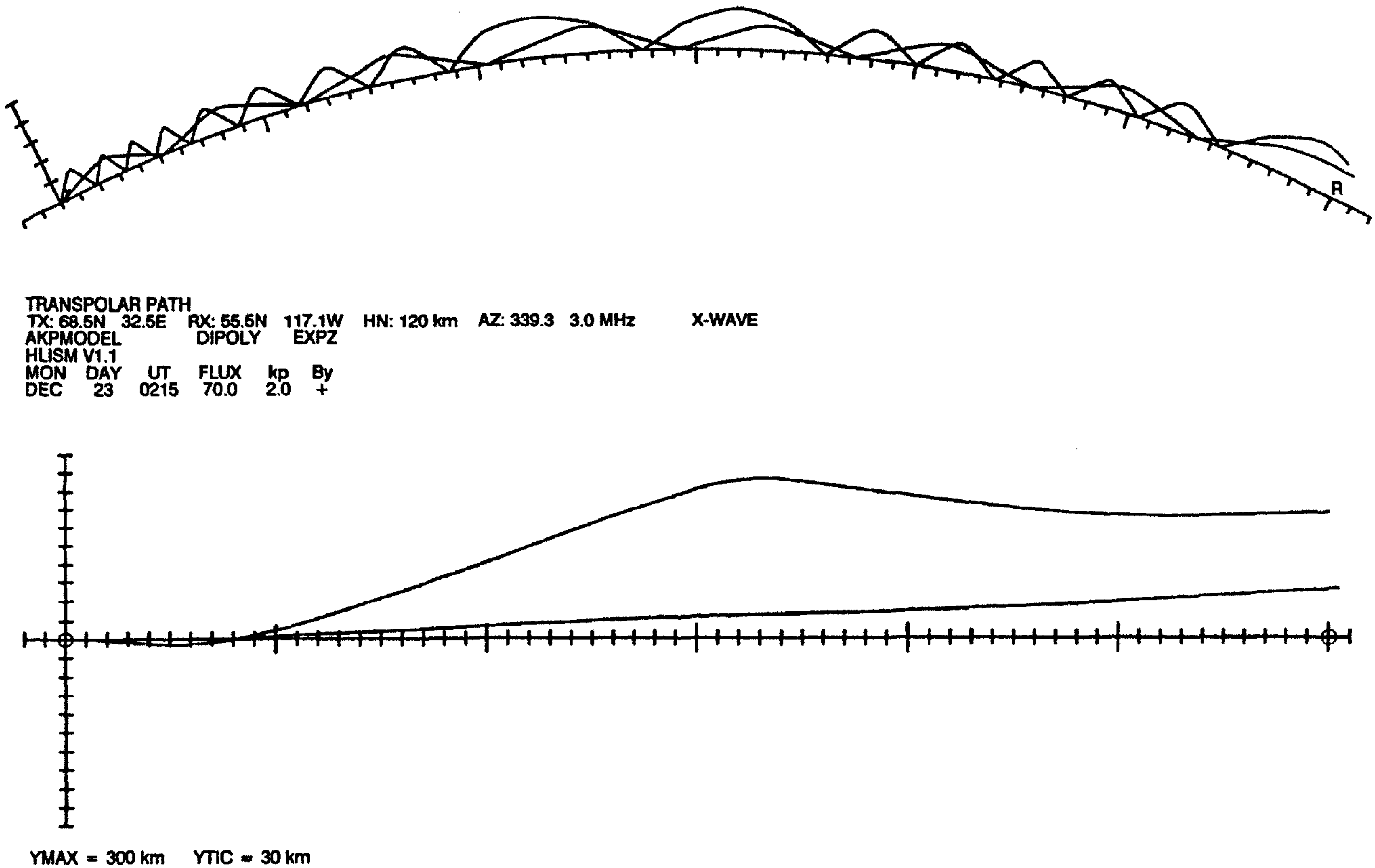

Figure 4. Plots of the ray paths for the extraordinary ray at 3 MHz in the vertical plane passing through the transmitter and the receiver (top panel) and in the horizontal plane (bottom panel). The elevation angles are 20° and 50°.

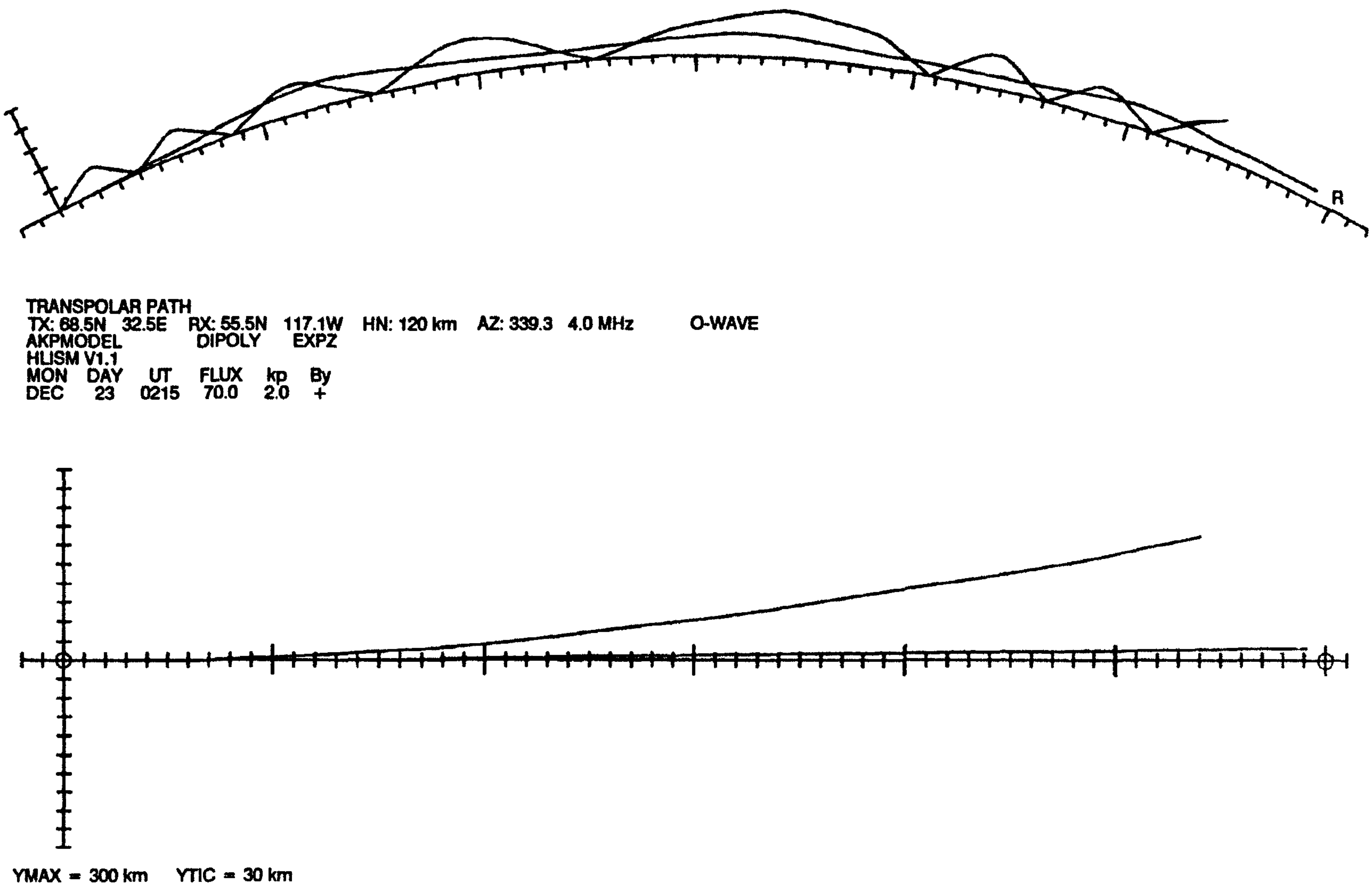

Figure 5. Plots of the ray paths for the ordinary ray at 4 MHz in the vertical plane passing through the transmitter and the receiver (top panel) and in the horizontal plane (bottom panel). The elevation angles are 0° and 30°.

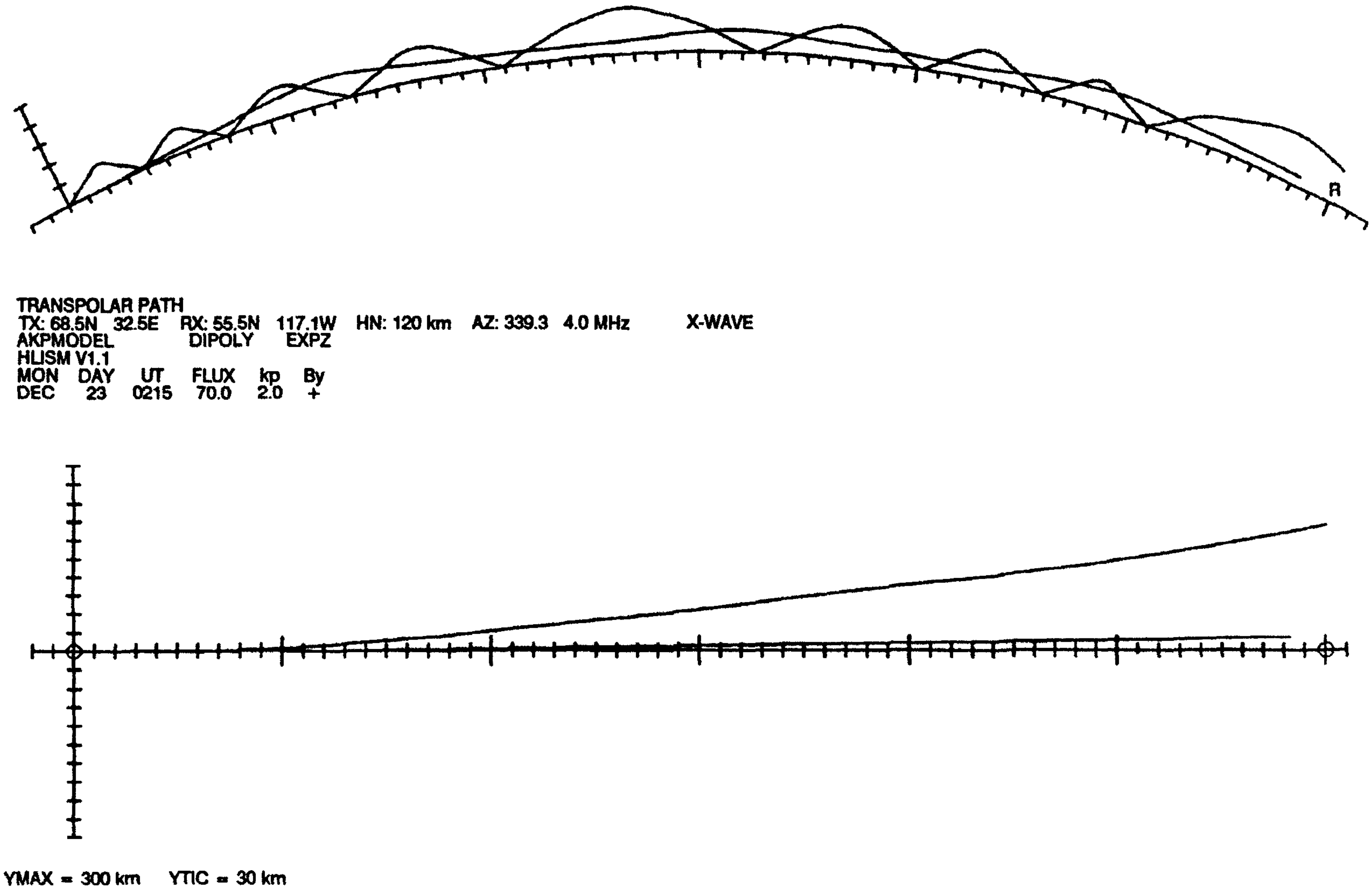

Figure 6. Plots of the ray paths for the extraordinary ray at 4 MHz in the vertical plane passing through the transmitter and the receiver (top panel) and in the horizontal plane (bottom panel). The elevation angles are 0° and 30°.

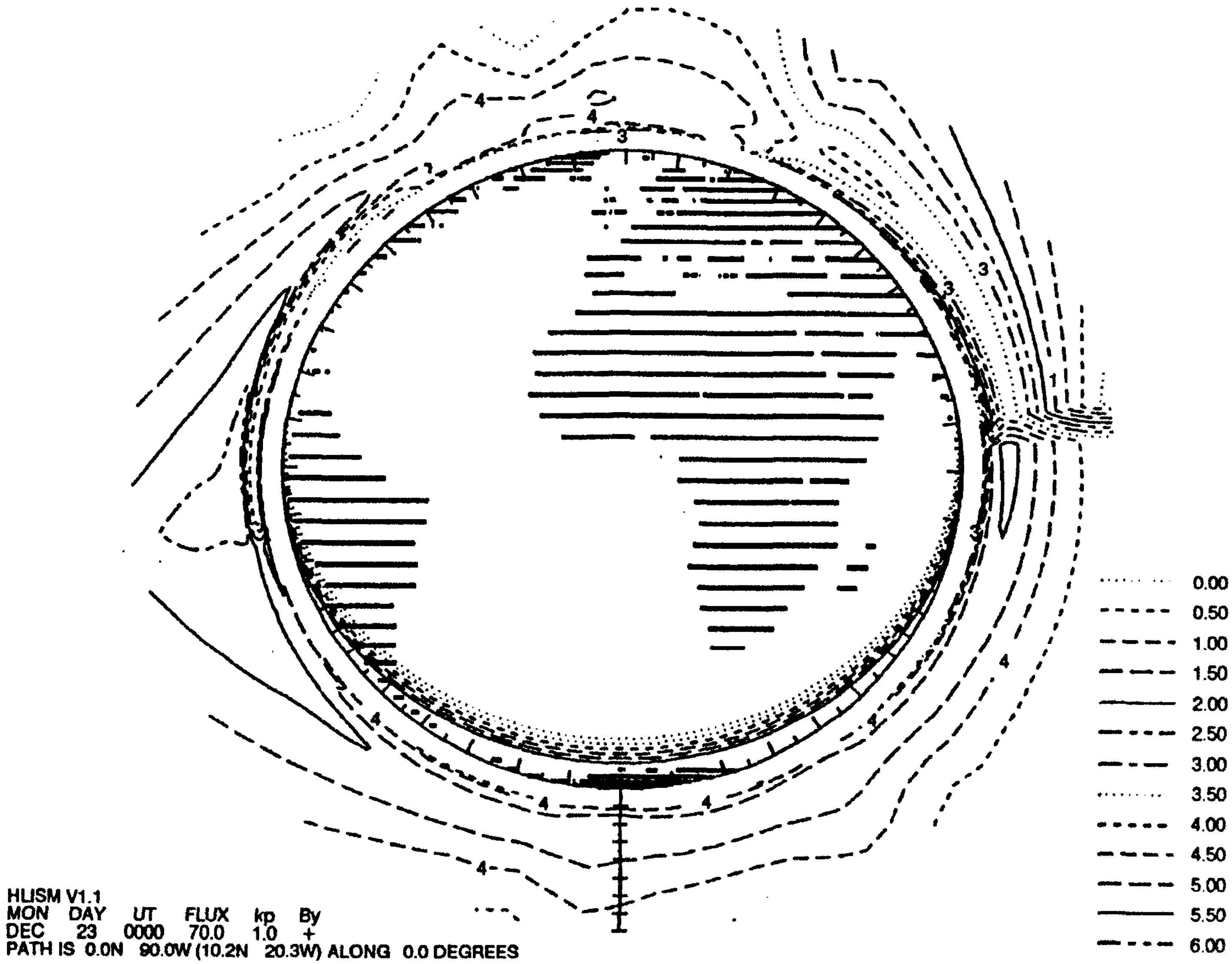

Figure 7. Plot of global contours of plasma frequency in a constant meridian. The vertical scale is exaggerated to show the contours.

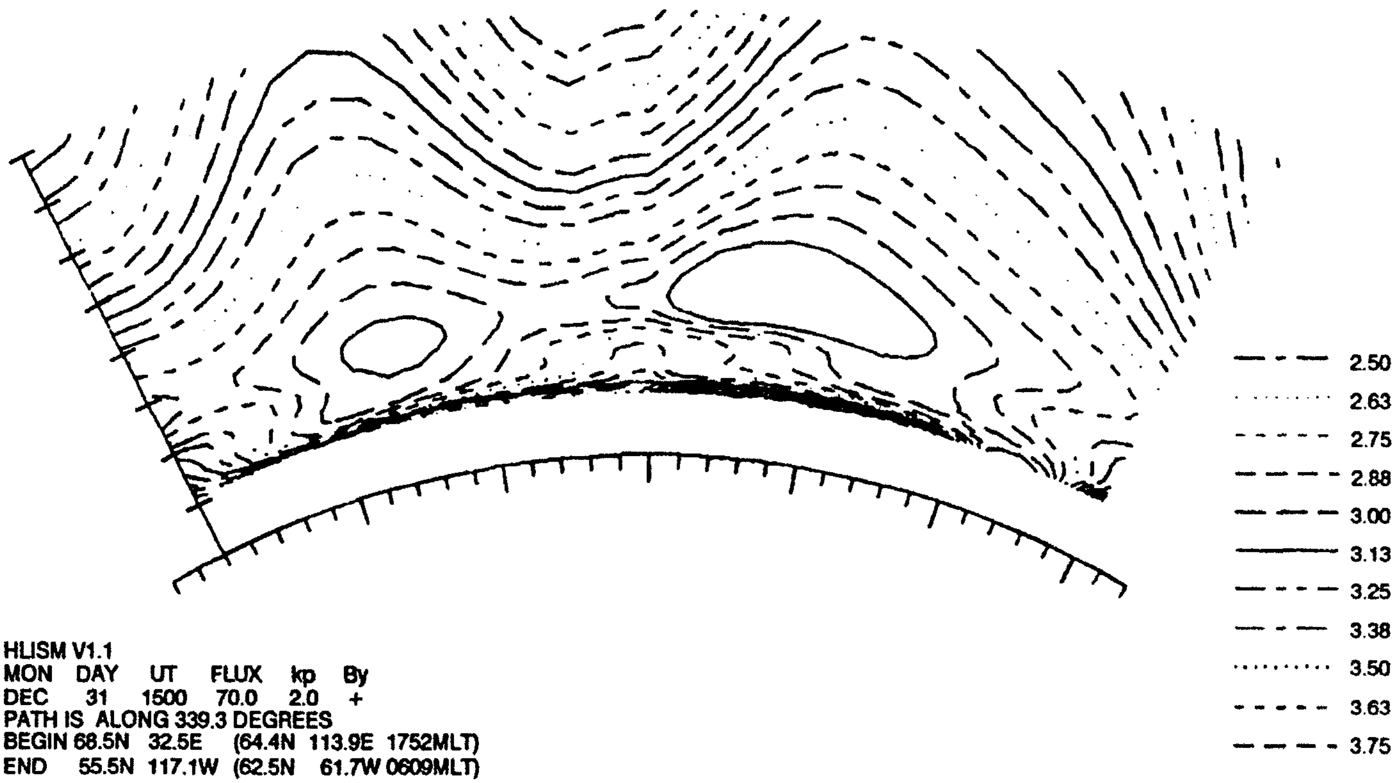

Figure 8. Plot of contours of plasma frequency in a plane defined by a plane passing through a transmitter and a receiver.

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The High-Frequency Benchmark is a computer code being developed to employ a sophisticated ray tracing program coupled with a state-of-the-art ionospheric model of the user's choice. The merging of these two major components depends critically on the development of a spatial smoothing routine that accepts arbitrary ionospheric models as input. Such a spatial smoothing routine was developed and implemented in the Benchmark. This report describes improvements and enhancements to that computer program.

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